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A Bi-Objective Sustainable Vehicle Routing Optimization Model for Solid Waste Networks with Internet of Things

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Abstract
Waste production is growing in most communities due to population expansion. Given the stated issue, managing the Solid Waste (SW) created worldwide would be vital. Effective Waste Management (WM) is essential to preserving the environment and lowering pollution. It aids in resource preservation, greenhouse gas emission reduction, and ecosystem protection. Additionally, the promotion of public health and sanitation is significantly aided by WM procedures. This study presents an integrated procedure to enhance the operations of a WM network for recycling SW. We propose a mathematical model to find the optimal sustainable vehicle routes, allocation, and Sequence Scheduling (SS) problem in the recycling industry to reduce costs and CO\textsubscript{2} emissions and increase job opportunities. The fundamental innovation of this work is considering waste-vehicle and waste-technology compatibility and Internet of Things (IoT) systems in the model to decrease CO\textsubscript{2} emissions and identify compatible waste for recycling centers to produce more final products. An LP-metric and an Epsilon Constraint (EC) approach are used to solve the suggested model. By comparing the two approaches, we have found EC performs better in results and CPU time. As a result, various test problems of different sizes are offered. Accordingly, sensitivity analyses are recommended to assess the suggested model’s effectiveness. Using vehicles compatible with waste reduces CO\textsubscript{2} emissions. Utilizing IoT technology and optimization methods makes it feasible to save costs (20\%), have a less destructive impact on the environment (36\%), and ultimately increase the sustainability of the WM process.

Keywords: Optimization; Waste management; Vehicle routing; Scheduling; Sustainability; Internet of Things.

1. Introduction
Waste is a form of solid, liquid, or gaseous substance produced by human activity, and these goods are worthless and redundant in the eyes of the customer (Gabrielli et al. 2018). SW, Industrial trash, Medical Waste (MW), Waste from electrical equipment, agriculture, construction, and wastewater make up the

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majority of trash. SW accounts for a significant amount of trash generated globally each day by numerous urban areas, including residential, organizational, and service centers (Sharma et al., 2019). Today, as a result of increased population expansion, emerging industries in countries, growing urbanization, economic development, and alterations in living standards (Mamashli et al., 2021) have all led to an increase in SW generation globally (Mohsenizadeh et al., 2019; Hannan et al., 2020; Rekabi et al., 2022). The rising volume and variety of this trash (Guerrero et al., 2013; Yousefloo and Babazadeh et al., 2019) have made collection and disposal problematic.

Typical disposal techniques, such as burying them underground or open dumping, are also prohibited (Dharam Singh et al., 2019), or burning them is ineffective in today's culture because they cannot avoid the spread of environmental contamination produced by chemical and microbiological waste. Consequently, the notion of Solid Waste Management (SWM) evolved gradually. Furthermore, it has lately become one of the most serious issues facing all nations in terms of decreasing their impacts on the ecosystem and the volume of them. Moreover, they include valuable components that may be repurposed for new goods or recovered for energy resources, which has significant economic and environmental benefits (Nanda and Berruti, 2017), specifically, lowering the expense of collecting and the environmental degradation caused by trash transportation and disposal. As a result, governments have determined that SW should encompass all elements of sustainable development, which is explored in three primary dimensions: environmental, economic, and social (Yadav and Karmakar 2019; Rekabi et al., 2021; Caramia and Pizzari 2023; Rekabi et al., 2023). At the same time, that is the ideal way to address the key parts of this problem. Thus, recently, the study of SWM has become an interesting topic for many scholars. Furthermore, several scholars have highlighted WM as a serious issue in the context of a growing economy (Shammi et al., 2021; Ilyas et al., 2020; Palmer et al., 1997; Afsharian 2023). In order to maintain excellent health, well-being, and environmental sustainability, emergency disposal of SW in a timely, organized and efficient manner is required.

In recent years, there has been a growing concern regarding the efficient and sustainable management of SW (Ng et al. 2020). As the population continues to grow and urban areas expand, it has become increasingly crucial to address the challenges associated with the collection and transportation of waste materials (Mousavi et al. 2023; Abubakar et al. 2022; Perkumiene et al. 2023). To tackle these issues, the integration of IoT technology into the SWM network offers promising solutions. The SWM network's key stage is suitable transportation and collection from the generating node to a recovery center or disposal area while lowering expenses and environmental pollutants. In different Time Periods (TPs), the amount of waste may increase or decrease. One efficient method to handle this issue is by developing a Supply Chain (SC), which requires a precise information system and intelligent planning (Shirazi et al., 2021). For
example, managers can use the IoT system to trace supply waste. The IoT enables connectivity between various electronic equipment through various identification methods.

The Vehicle Routing Problem (VRP) is also one of the most effective strategies for collecting and delivering SW in order to get optimal solutions for decreasing transportation expenses and environmental pollution (Kuo and Wang, 2011; Rawhoudine and Bacar, 2021). After that, one method of recycling to recover SW is to reuse it or its components (Eriksson et al., 2005). It might also be utilized as an energy resource with recycling techniques (Mamashli et al., 2021). As a result, the recycling procedure is a remarkable way to evolve sustainability in that it may reduce environmental impacts and economic expenses while also boosting human socialites' enjoyment, so waste recovery is a significant technique in SWM that can lead to recovering valuable materials.

According to the literature that will be evaluated in Section 2, much work has been done in the waste area because SWM has a vital role in people’s lives. Even though there are several gaps in this field, So, in this work, we have developed a new model named location allocation VRP with robot scheduling in a Recycling Center (RC), considering IoT systems and vehicle and technology compatibility in the RC. The purpose of this work is to decrease expenses, CO2 emissions, and increase job opportunities. Overall, this research intends to contribute to the optimization of SW processes by leveraging IoT technology and integrating sustainability principles. The bi-objective VRP will enable decision-makers to boost the efficiency and effectiveness of waste collection, reduce expenses, and minimize the overall environmental impact associated with SW transportation. Finally, the research questions are as follows:

1. How can sustainable vehicle routing optimization model for SW Networks with IoT be designed?
2. How can IoT system minimize CO2 emissions?
3. How much products is generated with using IoT system?

The remainder of the work is designed as follows: A literature summary is described in Section 2. Section 3 illustrates the description of the problem and the model formulation. Section 4 introduces solution approaches to solve the developed model. Section 5 examines numerical examples to measure the model’s performance and endorses model validation. Some sensitivity analyses are conducted on important parameters in Section 6. Eventually, Section 7 presents a conclusion and future offers.

2. Literature review

The generation of SW is an inescapable byproduct of human activity, and its management has a detrimental impact on both human and environmental health (Vinti et al., 2021). Cities tasked with safeguarding their residents from trash have a problem with these two inclinations. Many works have been conducted to tackle many difficulties in the SWM network, such as optimization of site facilities, VRPs, and choosing appropriate technologies for trash reusing, and investigating various elements of the problem of sustainability in backward logistics, by employing optimization techniques and mathematical
formulations all across the world. Significant current work will be examined, some of it on SWM, in the areas of facility location problems, VRP, Inventory Problem (IP), or the combination of these challenges as follows:

Yadav and Karmakar (2019) developed a model to determine the best location for station facilities in SW, with the goal of lowering total SWM expenses in India. Tirkolaee and Aydin (2021) suggested a location-allocation-IP on the SW network, including collection and disposal, with the goal of diminishing the overall expenses of the network, which included founded sites, collection, transportation, processing, delay of uncollected waste, and raising CO₂ emissions. Asefi et al. (2020) provided a Location-Routing Problem (LRP) for gathering and delivering waste in the SW network to diminish the overall expenses of founding facilities and waste transportation across centers. They then used a meta-heuristic method to determine the optimal number of facilities and truck routes and ultimately tested the model's performance in a Case Study (CS). Rabbani et al. (2021) devised LRP and IP for sustainable WM. Their approach addressed three facets of a sustainable system, aiming to reduce overall expenses, carbon emissions, and total time dedicated to waste collection and processing. Ranjbari et al. (2021) mapped the COVID-19-related scientific production in the field of WM. They constructed a Circular Economy (CE) model incorporating all activities, from planning to deployment. Haq et al. (2023) provided the shortest CE loop, which included the phases of collection, sorting, redesigning, re-cutting, and sewing. They used the CE notion of 'reusing' to handle pre-consumer garbage in a sustainable manner.

Various researches on the sustainability aspects of SW have been conducted in the past few years. For example, Farahbakhsh and Forghani (2019) explored a LRP with the goal of minimizing overall expenses and carbon emissions and enhancing social service in the SW system. In response to the COVID-19 outbreak, Sagnak et al. (2021) illustrated a mixed-integer sustainable model for WM. They considered decreasing environmental dangers as well as transit time. Furthermore, the majority of scholars have been fascinated by developing mathematical models for SW systems in an uncertain environment. Akbarpour et al. (2021) explored SWM in an industrial city using a stochastic model. They reduced total transportation expenses while increasing income from repurposed garbage. Eren and Tuzkaya (2021) constructed a multi-objective model for WM in the pandemic under uncertainty. Their model determined the most secure and fastest routes for collecting MW in a real CS. Mamashli and Javadian (2020) investigated the disaster WM problem through synchronous consideration of sustainability and resiliency under hybrid uncertainty. Joneghani et al. (2022) addressed the sustainable Location-Allocation (LA) problem in MW management under uncertainty. Tushar et al. (2023) assessed the crucial difficulties of efficient and sustainable MW management to lessen the consequences of the disruptions generated by crises like the epidemic in developing nations.
As previously stated, the employment of effective waste processing technologies for recycling, reuse, or treatment, and eventually sanitary disposal, is a key component of the SWM system. As a result, various studies have highlighted this aspect of the SW system. For instance, Qazi et al. (2018) evaluated waste-to-energy conversion solutions for various SW systems with economic and environmental goals like trash reduction, CO₂ emissions reduction, and enhanced landfill casting. Shahnazari et al. (2020) used decision-making approaches to assess the optimum recovery energy systems for obtaining energy resources from SW. Hameed et al. (2021) designed a hybrid treatment SW technology with biomass to produce energy and recovery resources from them on a sustainable WM system. Sazvar et al. (2022) addressed a scenario-based model to structure a sustainable closed-loop pharmaceutical supply chain considering and manufacturer’s brand and WM, which evaluates the backup flows of expired medications. Govindan et al. (2022) applied congestion to manage the waiting time of trucks carrying infectious waste in treatment centers for circular medical WM under uncertainty.

Due to its potential for revolutionizing a number of industries, the idea of the IoT has attracted a lot of attention in recent years. One area where IoT can have a substantial impact is in optimizing Vehicle Routing (VR) in the SWM network. Yadav et al. (2017) suggested an IoT-based smart WM solution for India in areas affected by COVID-19. Khoa et al. (2020) suggested a new approach that efficiently achieves WM by forecasting the probability of the waste level in trash bins by utilizing Machine Learning (ML) and graph theory. Khan et al. (2021) introduced an effective solution for smart WM using ML and the IoT. Yu et al. (2021) investigated the vehicle path optimization using IoT technology and intelligent algorithms. Khoshsepehr et al. (2023) addressed industrial WM difficulties and provided smart solutions to efficiently handle these challenges. Seker (2022) assessed smart garbage collection systems based on IoT regarding unknown parameters using improved Entropy metric and the Multi-Criteria Decision Making (MCDM) technique for the Istanbul municipal government. Chioatto et al. (2024) benchmarked the performance of municipal SWM in 167 regions during the period from 2008 to 2013. Their findings show a yearly reduction in the coefficient of variation of 3.6%. Sharma et al. (2024) investigated several policies and legislation developments on the end-of-life of photovoltaic modules in various regions of the world, to identify gaps for further assessment. The findings demonstrated the importance of the sustainable management of photovoltaic panels at end-of-life.

As decided, several features have not been studied earlier, and we will illustrate some of them here:

- There has not been an examination of a simultaneous IoT-enabled LA-VRP with a robotic sequencing schedule mathematical formulation
- There has been no consideration of location or recycling technology for each site in SWM
- No unique technique or procedure for recycling and producing new goods for each sort of garbage has been created
• Considering waste-vehicle and waste-technology compatibility and using an IoT system in the model to identify compatible waste for RC simultaneously to enhance routing efficiency and reduce environmental impact

• Using two MCDM approaches named LP-metric and EC simultaneously

Consequently, this work introduces a new model formulation, which is a LA-inventory-VRP with scheduling robot integrated bi-objective mixed integer programming, to choose the best location, recycling technologies, and collecting routes in each TP, as well as clarify the amount of the created items for SWM networks by using waste-vehicle and waste-technology compatibility and an IoT system in the mathematical model to improve route efficiency, WM, and resource allocation.

3. Problem overview and formulation

3.1. Problem explanation

This work illustrates an organized procedure to boost the operations of a WM network for recycling waste. Thus, in this work, a bi-objective multi-depot model to find the optimal vehicle routes and allocation, as well as scheduling problems in the RC, with the aim of diminishing overall expenses, CO₂ emissions, and increasing potential employment is developed. As illustrated in Figure 1, each vehicle begins its journey from one depot and then gathers its compatible waste items from the generation nodes before returning to the same depot from which it began its journey. Then, utilizing the IoT system, it proceeds to the designated RCs to dispose of each type of garbage in a suitable facility. Each facility features equipment that is suitable for a certain type of trash. A specific product will be produced during the processing of each type of trash using the appropriate technology. In the RC, robots take action on garbage by following a specified schedule to create a new product in each RC. The RC that generates that sort of product meets the demands of each product. Waste can only be manipulated after it has been generated.
3.2. Problem assumptions

Several assumptions are explored in this study, which are as follows:

- Generation node’s locations have been identified.
- Amount of each form of recycling waste generated by a human in each TP is determined at random.
- Structure of the network is multi-depot.
- Wastes are segregated at generating nodes, and incomplete garbage collection is not permitted.
- Each facility should only receive the quantity of waste that can fit inside it.
- Vehicles are heterogeneous.
- Each facility can be served by a single technology
- Each vehicle could only visit each generating node once per time.
- Robots are unique and possess a wide range of abilities.
- Considering the IoT expense in the model to identify compatible waste for each RC.
- All parameters are deterministic.

3.3. Mathematical formulation

The mathematical model's sets, parameters, and variables are as follows.
Sets

\( G \) Set of generation's nodes indexed by \( g \)
\( D \) depot indexed by \( d \)
\( W \) Set of waste types indexed by \( w \)
\( K \) Set of vehicle types indexed by \( k \)
\( R \) Set of total RCs indexed by \( r \)
\( Q \) Set of different technologies of RCs; indexed by \( q \)
\( T \) Set of TPs; indexed by \( t \)
\( i, j \) Index of all nodes in the network
\( O \) Set of robots indexed by \( o \)
\( N \) Set of operations for each waste indexed by \( n \)

Parameters

\( \text{dis}_{dr} \) Distance between depot \( d \) and node \( r \)

\( c_o \) Transportation expense per unit of distance
\( f_rq \) Foundation expenses of a RC at node \( i \in r \) with technology \( q \)
\( p_{wqr} \) Expenses of processing each unit of waste \( w \) with technology \( q \) at RC \( r \)
\( so_{wqr} \) Financial value of each waste \( w \) with technology \( q \) at RC \( r \)
\( \text{dem}_{iw} \) Amount of waste \( w \) at node \( i \in g \) in TP \( t \)
\( nr_{iq} \) Number of workers required in recycling operations at node \( i \in r \) with technology \( q \)
\( \text{cap}_{kw} \) Capacity of vehicle \( k \) that is accommodate with waste \( w \)
\( \text{em}_k \) The \( \text{CO}_2 \) emission of vehicle \( k \) per unit of distance
\( a_{wq} \) Quantity of waste created by processing waste \( w \) with technology \( q \)
\( d_{wqtr} \) Overall demand for the product created by waste \( w \) with technology \( q \) in TP \( t \) in RC \( r \)
\( ec \) The maximum allowable overall \( \text{CO}_2 \) emission in each TP
\( \text{com}_{wq} \) 1 if waste \( w \) is compatible with technology \( q \); 0 otherwise
\( \text{veh}_{kw} \) 1 if waste \( w \) is accommodate with vehicle \( k \); 0 otherwise
\( M \) Great number

\( GD \) Maximum number of depots and generation nodes
\( pt_{wn} \) Processing time of recycling activity on waste \( w \)
\( MR \) A number of vehicles for transfer waste \( w \) to RC
\( C_{iot} \) Fix expense of establishing the required IoT system
Variables

\( x_{ijk\tau} \) If vehicle \( k \) travels from node \( i \) to \( j \) in TP \( t \); \( x_{ijk\tau} = 1, 0 \) otherwise

\( r_{rq} \) If a RC with technology \( q \) is opened in location \( r \); \( r_{rq} = 1, 0 \) otherwise

\( u_{ikt} \) Continuous variable for subtour elimination constraints

\( x_{rwt} \) Amount of waste \( w \) that arrival RC \( r \) in TP \( t \)

\( y_{dr} \) 1 If depot \( d \) assigned to RC \( r \), 0 otherwise

\( q^y_{dt} \) Amount of waste \( w \) which arrival to each depot

\( p_{d_{rwqf}} \) Quantity of product produced from waste \( w \) with technology \( q \) in RC \( r \) in TP \( t \)

\( s_{tw} \) Starting time of operation waste \( w \)

\( f_{tw} \) Finishing time of operation waste \( w \)

\( y_{rwnw}^{w_{n\prime}} \) 1 if the recycling operation of waste \( w \) occurs before the operation waste type \( w' \) by robot \( o \); 0 otherwise

\( z_{w} \) 1 if the recycling operation of waste \( w \) done by robot \( o \); 0 otherwise

\( z_{r} \) 1 if the appropriate system for IoT is founded in RC \( r \); 0 otherwise

Objective functions

The first OF minimize the overall expenses, which is illustrated in Equation (1). Equations (1a) – (1e) clarify how each component of the expense stated is determined.

\[
\text{Min } Z_1 = C\text{cost} + T\text{cost} + P\text{cost} - \text{Revenue} \tag{1}
\]

\[
\text{Revenue} = \sum_{r \in R} \sum_{q \in Q} \sum_{w \in W} s_{wqr} p_{d_{rwq}} \tag{1a}
\]

\[
C\text{cost} = \sum_{r \in R} \sum_{q \in Q} f_{r_{rq}} r_{rq} \tag{1b}
\]
The revenue illustrated in Equation (1a) is the overall revenue made by selling various final products. \( C_{\text{cost}} \) as shown in Equation (1b) is the overall expense of installing recycling facilities is referred to as the capital cost. \( T_{\text{cost}} \) shown in Equation (1c), is the transportation expense. \( P_{\text{cost}} \) shown in Equation (1e) is the processing and IoT expenses at RCs.

\[
T_{\text{cost}} = \sum_{d=1}^{D} \sum_{o=1}^{O} \sum_{r=1}^{R} c_{do} \text{dis}_{dr} \gamma_{dr} 
\]

\[
P_{\text{cost}} = \sum_{r \in R} \sum_{w \in W} \sum_{q \in Q} \sum_{t \in T} p_{wqr} \alpha_{wq} \rho_{drwt} \text{com}_{wq} + \sum_{r \in R} \text{Ciot} \ ziot \_r 
\]

The revenue illustrated in Equation (1a) is the overall revenue made by selling various final products. \( C_{\text{cost}} \) as shown in Equation (1b) is the overall expense of installing recycling facilities is referred to as the capital cost. \( T_{\text{cost}} \) shown in Equation (1c), is the transportation expense. \( P_{\text{cost}} \) shown in Equation (1e) is the processing and IoT expenses at RCs.

\[
\text{Max} \ Z_2 = wn \left( \frac{\sum_{r \in R} \sum_{q \in Q} n_{rq} - \min n_r}{\max n_r - \min n_r} \right) + wc \left( \frac{\max c_o - \sum_{r \in R} \sum_{d \in D} \sum_{k \in K} e_{mk} y_{dr}}{\max c_o - \min c_o} \right) 
\]

The second OF seeks to raises the job opportunities in each RC and decreases CO2 emissions between generation nodes and depots.

\[
\sum_{d \in D} \sum_{r \in R} \sum_{k \in K} x_{ijkt} \text{dis}_{dr} \text{em}_{k} \leq e_{t} \quad \forall t \in T 
\]

\[
\sum_{j \in G} x_{ijkt} = 1 \quad \forall i \in D, k \in K, t \in T 
\]

\[
\sum_{i \in D \cup G} x_{ijkt} = 1 \quad \forall j \in G, k \in K, t \in T 
\]

\[
\sum_{r \in R} \sum_{d \in D} \sum_{k \in K} x_{ijkt} \leq \sum_{w \in W} \sum_{q \in Q} \text{veh}_{kw} \text{com}_{wq} \rho_{qr} \quad \forall r \in R 
\]

Equation (3) assures that the amount of CO2 emissions from vehicles should not exceed the allowed range in each TP. According to Equation (4), the starting place for all vehicles at the beginning of each TP is a depot. Equation (5) ensures that each vehicle's journey remains continuous by entering and departing the same generating node. According to Equation (6), all generation nodes are visited precisely once. Equation (7) depicts the compatibility between vehicle waste and waste technologies. This Equation guarantees that each form of garbage is delivered by the appropriate vehicle.

\[
u_{ikt} - u_{jkt} + GD \times x_{ijkt} \leq GD - 1 \quad \forall i, j \in G, k \in K, t \in T 
\]
\[
\sum_{d \in D} \sum_{w \in W} dem_{iwt} \cdot veh_{kw} \leq u_{ikt} \\
\leq \sum_{j \in D} \sum_{w \in W} veh_{kw} \cdot cap_{kw} \\
q_{d}^{w} = \sum_{i \in G} \sum_{k \in K} \sum_{t} x_{ijkt} \cdot dem_{iwt} \\
\sum_{r \in R} \sum_{t \in T} x_{rwt} = \sum_{d \in D} \sum_{r \in R} \sum_{q \in Q} q_{d}^{w} \times rr_{rq} \times com_{wq} \\
(pd_{rwt}) = d_{wqr} \cdot rr_{rq} \cdot com_{wq} \\
(st_{wn} + pt_{wn}) + MR(1 - yr_{wnw'n'o}) \leq f_{twn} \\
(st_{wn} + st_{wnr}) + MR(1 - yr_{wnw'm'o}) \geq pt_{wnr} \\
\sum_{o \in O} z_{wno} \leq 1 \\
yr_{wnw'm'o} \leq z_{wno} 
\]

Equations (8) and (9) are sub-tour eliminations. Furthermore, these limitations ensure that a collection vehicle’s load does not exceed its assigned capacity. The amount of each sort of waste that enters each depot is calculated using Equation (10). According to Equation (11), the demand for the goods allotted to the RCs should be met throughout each TP. The amount of each sort of waste that enters each RC is determined by Equation (12). Equation (13) given the completion of time operating type \(n\) on the waste type \(w\). The sequence in which each waste’s recycling processes are carried out is shown in Equation (14). Equation (15) prevents one robot from performing two tasks simultaneously. The maximum number of robots that must process each waste is determined by Equation (16). Equations (17) outline a series of tasks that each robot must do.

\[
\sum_{q \in Q} rr_{rq} \leq 1 \\
\forall r \in R 
\]
\[
\sum_{r \in R} \sum_{q} r_{rq} \geq \text{com}_{wq} \quad \forall w \in W, q \in Q \tag{19}
\]
\[
\sum_{ijkt} x_{ijkt} = 0 \quad \forall k \in K, t \in T \tag{20}
\]
\[
\sum_{w} \sum_{j \in D, i \in D} p_{d_{wqt}} \leq \sum_{w} \left( \vartheta q_{1}(1 - \text{ziot}_{r}) \right) \text{com}_{wq} x_{r_{wqt}} + \vartheta 2 q (1 - \text{ziot}_{r}) \quad \forall r \in R, q \in Q, t \in T \tag{21}
\]
\[
x_{ijkt}, r_{qr}, y_{dr}, z_{wno}, y_{rwwnw} = \{0,1\} \quad \forall i, j \in g, d \in D, r \in R, w \in W, n \in N, o \in O \tag{22}
\]
\[
u_{ikt}, f_{twm}, s_{wn}, x_{iwt} \geq 0 \quad \forall i \in g, k \in K, t \in T, w \in W, n \in N \tag{23}
\]

Equation (18) reveals that each RC could only use one sort of technology. Equation (19) guarantees that a facility that is compatible with each product should be founded. Equation (20) depicts those vehicles that should not travel between depots. Equation (21) calculates the amount of waste recycled in RC with technology compatibility according to whether IoT is established or not. Equations (22) and (23) display each variable's range.

4. Solution methodology

The developed model is solved for five problems with two LP-metric and EC approaches.

4.1. LP-metric procedure

One of the most commonly used procedures in the literature on multi-objective issues is the LP-metric approach. With this approach, we aim to reduce the OFs' deviations from their ideal values (Rekabi et al. 2021).

In the extensive criteria technique, the aggregate Equation (24) minimizes after individual solutions for each OF's optimality are determined. The ideal amount of the \( j \)th OF is \( Z_{j}^{*} \), and \( w_{j} \) illustrates the significance of the \( j \)th OF. The reader is referred to additional research into these methods (Yu and Zeleny, 1974; Hwang and Masud, 1979). The following structure represents the LP-metric mathematical model:

\[
\min Z_{1}(x) \\
\min Z_{2}(x) \\
\vdots \\
\min Z_{j}(x) \\
\text{s.t.:} \\
X \in x
\] \[
- \left\{ \min D_{p} = \left( \sum_{j=1}^{j} w_{j} \left( \frac{Z_{j}(x) - Z_{j}^{*}}{Z_{j}^{*}} \right) \right) \right\} \\
\text{s.t.:} \\
X \in x
\]

4.2. Epsilon-constraint approach
One of the most effective and accurate multi-objective optimization strategies is the EC approach. In the EC approach, one of the OFs will be chosen to be optimized, and the remaining OFs will serve as constraints (Eydi and Bakhtiari, 2017). The overall form of the EC method is represented below:

\[
\begin{align*}
\min & \quad Z_1(x) \\
\min & \quad Z_2(x) \\
\vdots & \\
\min & \quad Z_j(x) \\
\text{subject to} & \quad x \in X \\
& \quad Z_2(x) \leq \varepsilon_2 \\
& \quad \ldots \\
& \quad Z_j(x) \leq \varepsilon_j
\end{align*}
\]

(25) \quad (26) \quad \ldots \quad (27) \quad (28) \quad (29)

where, \( X \) represents the space of feasible solutions, and \( \varepsilon_j \) is the upper bound of \( j \)th OF. The ability to reach effective spots on a non-convex Pareto curve is one benefit of the EC technique. As a result, the decision maker can alter the upper bounds \( \varepsilon_j \) to find the best solution (Khalili-Damghani et al., 2013).

5. Numerical example

5.1 Computational experiment

To show the practicality of the suggested model, five test problems are created and solved. The problems have various sizes. To make everything more realistic, all parameters follow a uniform distribution, and we round these values to better depict the result better. Table 1 provides information on the features of the problem we are considering, and Table 2 provides information on the parameter values. The LP-metric and EC approaches are used to solve each problem. The suggested method is implemented with the GAMS software on a laptop with an Intel (R) Core (TM) i7-10750H CPU @ 2.60 GHz. The model is presented in this work provides the shortest route for vehicles with the most optimal expense. Also, the amount of pollution emission will be minimized, and the number of jobs created will also be maximized.

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<td>d</td>
<td>No. of depot</td>
<td>3, 3, 4, 5, 5</td>
</tr>
<tr>
<td>w</td>
<td>No. of waste</td>
<td>4, 4, 4, 4, 4</td>
</tr>
<tr>
<td>k</td>
<td>No. of vehicle</td>
<td>3, 3, 3, 4, 4</td>
</tr>
<tr>
<td>t</td>
<td>No. of TPs</td>
<td>3, 4, 4, 5, 6</td>
</tr>
</tbody>
</table>
### Table 2. Related parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dis_{tr}$ (kilometers)</td>
<td>~uniform (10,50)</td>
<td>$cap_{kw}$ (kilogram)</td>
<td>~uniform (2000,3000)</td>
</tr>
<tr>
<td>$c_o$ (dollar)</td>
<td>~uniform (300,1000)</td>
<td>$mr$ (number)</td>
<td>~uniform (50,200)</td>
</tr>
<tr>
<td>$pr_{wqr}$ (dollar)</td>
<td>~uniform (300,1500)</td>
<td>$em_r$ (ppm)</td>
<td>~uniform (10,50)</td>
</tr>
<tr>
<td>$fr_{rq}$ (dollar)</td>
<td>~uniform (1000,2500)</td>
<td>$rc_r$ (kilogram)</td>
<td>~uniform (300,2000)</td>
</tr>
<tr>
<td>$so_{wqr}$ (dollar)</td>
<td>~uniform (100,200)</td>
<td>$alpha_{wq}$ (kilogram)</td>
<td>~uniform (10,500)</td>
</tr>
<tr>
<td>$dem_{wtr}$ (kilogram)</td>
<td>~uniform (500,600)</td>
<td>$dt_{wqr}$ (number)</td>
<td>~uniform (100,200)</td>
</tr>
<tr>
<td>$nr_{rq}$ (number)</td>
<td>~uniform (50,500)</td>
<td>$e_t$ (ppm)</td>
<td>~uniform (2500,2700)</td>
</tr>
<tr>
<td>$GD$ (number)</td>
<td>~uniform (10,23)</td>
<td>$pt_{wn}$ (min)</td>
<td>~uniform (10,50)</td>
</tr>
</tbody>
</table>

### 5.2. Result

The five sample problems from the previous part are solved in order to validate the recommended model in this section. As mentioned earlier, this work presents a two-objective mixed integer nonlinear mathematical model so that decision makers can find the best path for the waste trucks to move. Also, in this study, all dimensions of sustainability in model formation are considered. In addition, the model helps decision makers identify the most optimal place to build recycling facilities.

Some parameters are altered, and the reaction of the model is assessed. To achieve this, numerical findings from the LP-metric and EC approaches are examined in relation to the key metrics: first OF value ($Z_1$), second OF value ($Z_2$), CPU-time. Table 3 displays the numerical outcomes. It is evident that the best model is the one with the lowest mean and standard deviation. Table 3 demonstrates that the EC outperforms the LP-metric approach, which shows the superiority of the EC over the deterministic model.

### Table 3. Comparing findings of two approach

<table>
<thead>
<tr>
<th>The number of problems</th>
<th>Run with LP-metric</th>
<th>Run with EC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Z_1$</td>
<td>CPU-times</td>
</tr>
<tr>
<td>1</td>
<td>9.647117E+8</td>
<td>003</td>
</tr>
<tr>
<td>2</td>
<td>1.134563E+9</td>
<td>006</td>
</tr>
<tr>
<td>3</td>
<td>1.157713E+9</td>
<td>065</td>
</tr>
</tbody>
</table>
6. Sensitivity analysis

Several sensitivity assessments are performed to validate the suggested model and examine the influence of key factors on the optimal solutions.

6.1. Advantages of the IoT system

This part focuses on analyzing how the IoT system affects the suggested problem. As shown in Figures 2a and 2b, the IoT system affects the number of products generated from waste and increases them. Furthermore, according to this figure, the IoT system significantly reduces the expenses associated with logistical activities and increases revenue by purchasing more products that were generated from waste.

![Figure 2a. Assessing the impact of the IoT on revenue](image-url)
6.2. Change in demand value

To analyze the demand, the Objective Function values are tested in several modes. Figure 3 depicts the outcomes of the OFs by changing the demand. Based on Figure 3, the components’ expense expands as demand goes up first, but after passing a 30% rise in demand, the expense function decreases. And the number of job opportunities grows as more recycling facilities are utilized.

6.3. Change in capacity of compatible vehicle

This part focuses on analyzing how the capacity of vehicle affects the suggested problem. As shown in Figure 4, the capacity of vehicle affects the number of products generated from waste and increases them.
So, this change increases the revenue of the network by purchasing more products that were generated from waste and decreases the total expense by using fewer vehicles, respectively. Moreover, when the capacity of vehicles increases, they transport more wastes, and CO₂ emissions decrease.

\[ \text{Revenue} = \text{SWM problem} \times \text{productivity} \times \text{environmental compatibility} \]

\[ \text{Expense} = \text{vehicle cost} \times \text{technology compatibility} \times \text{IoT systems} \]

6.4 Managerial perspective

This section offers some insightful management and theoretical information. This work has investigated the SWM problem, considering sustainability, waste-vehicle and waste-technology compatibility, and IoT systems in the model to decrease CO₂ emissions and identify compatible waste for recycling centers to produce more final products. The proposed IoT-enabled WM system can assist managers in taking the required actions to accelerate operations by providing a comprehensive view of the problem of WM in the collection and recycling phases.

- Figures 2a and 2b show that, despite the expense associated with setting up the IoT system, it has resulted in considerable savings for collection and recycling expenses as well as an increase in income. Therefore, managers should be aware that while using new technology may appear expensive at first, doing so may really save logistical expenses, boost productivity over the long run, and enhance SC operations.

- Based on Figure 3, before 30% increasing the demand, the total expense increases. Based on this work, the first policy is capacity acquisition, which can be effective in controlling expenses. Another policy that managers can obtain is to use ML algorithms to predict demand and respond to customers in uncertain environment. Furthermore, as shown in Figure 3 by increasing demand, the number of job opportunities increases, which is a good result for the social aspect of sustainability.

![Figure 4. Analyzing the impact of changing vehicle capacity on revenue](image)
• As shown in Figure 4, the capacity of a vehicle affects the number of products generated from waste and increases them. So, this change increases the revenue of the network by purchasing more products that were generated from waste and decreases the total expense by using fewer vehicles, respectively. Moreover, when the capacity of vehicles increases, they transport more waste, and the network needs fewer vehicles, so CO\textsubscript{2} emissions decrease. Therefore, managers are suggested to help increase SW network resiliency by increasing the capacity of compatible vehicles.

7. Conclusion and future works

In order to create an effective SW network, this study creates a novel mixed-integer bi-objective mathematical model. SW plays a significant impact in people's lives. Compared to earlier times, this environmental concern can pose a substantially bigger threat to both human health and ecological equilibrium. Thus, a novel integrated multi-level model for a thorough SWM system at three levels of VR, disassembly SS and allocation of RCs to depot centers has been proposed in this study. The innovative idea presented in this work is utilizing waste-vehicle and waste-technology compatibility as an effective and useful strategy to diminish environmental issues and to use an IoT system in RC to identify compatible waste for each center to decrease CO\textsubscript{2} emissions and produce more products from waste. By incorporating IoT devices into the waste network, the suggested model aims to optimize the routing of vehicles to ensure sustainable and environmentally friendly WM practices. The paper likely describes how the model considers multiple objectives, such as minimizing overall expenses environmental impact of WM operations and maximizing job opportunities.

The suggested model offers several notable contributions. Firstly, it takes into account multiple objectives, promoting economic, social and environmental sustainability. Secondly, the incorporation of IoT technology allows for improved monitoring, data-driven decision-making, and optimization of WM operations. Finally, the paper highlights the application of this model in the context of the SW network, which is an important domain requiring efficient and sustainable solutions. For solving developed model, two multi-objective approaches, LP-metric and EC, were used to solve the given model in order to assess its efficacy. The performance of the suggested methods was verified by conducting some numerical examples. The findings illustrated that the recommended EC is capable of producing better results for this problem in a reasonable time by comparing mean and standard deviation in comparison with the LP-metric approach. Finally, by illustrating the findings of the problem and developing multiple sensitivity investigations, the effectiveness of the network was investigated. The findings contribute to the ongoing efforts to enhance WM practices, optimize resource allocation, and minimize environmental impact.

For next work, the following subjects are suggested:

• To tackle complex issues, it is advised to use heuristic and meta-heuristic algorithms
• It would also be beneficial to use stochastic optimization to solve the issue of uncertainty
• It would also be beneficial to take into account the ML algorithm to predict trash.
• Considering all aspects of Industry 5.0 would also be effective

Authors Contributions

Dr. Shabnam Rekabi: conceptualization, methodology, software, validation, original draft preparation, visualization.

Dr. Zeinab Sazvar: supervision, investigation, validation, reviewing and editing.

Dr. Fariba Goodarzian: Supervision, Reviewing, and Editing.

Statement of conflicting interest

The authors state that they don't have any known financial or personal conflicts that would have looked to affect the work covered in this work.

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**Declaration of Competing Interest**

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